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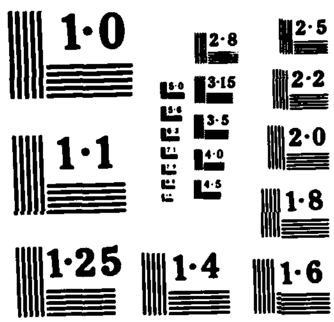

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PULSED POWER REQUIREMENTS FOR EM LAUNCHERS

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Summary

Both linear (railgun) and coaxial (mass driver, etc.) electromagnetic launchers (EMLs) are treated as time-varying impedances to determine the relationships between acceleration force, payload velocity, and power supply voltage and current. These relationships are then examined in the light of electromagnetic parameters associated with each EML type to establish a basis for determining and comparing power supply requirements for various EMLs.

Introduction

Electromagnetic launchers have been categorized by conductor geometry, similarity to conventional rotating electrial machines, and suitability for various applications. From a power supply viewpoint, it is useful to consider the relationship between the charging time or the time required to transfer the energy from the power supply to the launcher (t_c) and the launch time or the time required to transfer the total energy from the launcher to the projectile (t_ℓ). In this case EMLs divide neatly into three categories:

- those charged by the power supply prior to launch for which $t_c >> t_\ell$, such as the ARRADCOM solenoid gun,
- those that are actively driven by the power supply during launch for which $t_c = t_\ell$, such as the railgun and helical railgun; and
- those for which $t_c << t_\ell$, such as the mass driver and multi-stage induction accelerator.

In principle, launchers for which $t_c = t_\ell$ have intermediate voltage requirements and launchers of the $t_c << t_\ell$ type have the highest voltage requirements.

For the purpose of this discussion, the EML is considered to be the launch tube with its requisite conductors and the armature (movable conductor(s)). All energy storage, switching, and power conditioning devices external to the launch tube are considered to be parts of the power supply.

Force-Current-Voltage Relationships for EMLs

For virtually all EMLs, the force generated on the armature can be expressed as the derivative of the magnetic energy stored in the launcher with respect to length along the launcher (Eq. (1)).

$$F = -\frac{\partial W}{\partial x} = \frac{\partial}{\partial x}\left(\frac{1}{2} L_s I_s^2 + M I_s I_A + \frac{1}{2} L_A I_A^2\right) \qquad (1)$$

where
F = acceleration force on the armature (N)
W = magnetic energy stored in launcher (J)
x = length along launcher (m)
L_s = stator inductance for continuous accelerators or inductance of individual drive coils for discrete coil accelerations (H)
I_s tator current (A)
M = mutual inductance between stator and armature (H)
L_A = armature inductance (H)
I_A = armature current (A)

Assuming essentially constant driving current during the launch, Eq. 1 reduces to the simpler expressions in Table 1 for the various EML types.

Similarly, the back electromotive force, ε, (emf) of the EML can be expressed as the time derivative of the flux linkage, λ, in the launcher (Eq. 2).

$$\varepsilon = \frac{\partial \lambda}{\partial t} = \frac{\partial}{\partial t}(L_s I_s + M I_A) \qquad (2)$$

Equation 2 is also given for specific EML types in Table 1. For the railgun and helical railgun, the back emf can be considered to be the driving voltage required for an ideal (lossless) EML. The mass driver and induction accelerator, however, have an additional driving voltage requirement even for the ideal case. The stator of these two EMLs consistsof discrete coils that must be energized and deenergized in a time short compared to the transit time of the armature through their effective range (in order for the constant driving current assumption, and thus the constant acceleration approximation, to be valid). For the purpose of comparison in this paper, it is assumed that the stator coils in the mass driver and induction accelerator must be energized in the time required for the armature to travel a distance equal to the stator coil inductance length, ℓ, i.e., the distance between the drive coil and the peak of the mutual inductance gradient. This coil charging voltage can be expressed as shown in Eq. 3, where v is the armature velocity.

$$V_{charging} = L_s \frac{\partial I_s}{\partial t} \cong L_s \frac{I_s}{(\ell/v)} \qquad (3)$$

The solenoid gun, on the other hand, is charged by its power supply prior to launch, and thus the power supply voltage is determined only by launcher resistance, charging efficiency, and heating considerations.

Table 2 presents typical values for the driving inductance gradients of the various EMLs. It is not claimed that these are optimal values, but rather that they represent what has typically been achieved. The following analysis and modeling are sufficiently transparent to these assumptions that the effect of other values can be readily determined. Other assumptions listed in Table 2 make use of the observation that for coaxial EM accelerators, other than the solenoid gun, the magnetomotive forces (mmf) developed by the active stator and armature windings are approximately equal. This is generally true, since it makes little sense to expend power developing mmf that will not be opposed and therefore will not produce accelerating force. The solenoid gun is an exception to this general rule because the stator winding serves the dual purposes of storing the launch energy as well as providing the driving mmf.

Combining the relationships in Table 1 with the electromagnetic parameters and assumptions in Table 2 gives the ideal (lossless) current and voltage requirements for the various EMLs (see Table 3).

Figure 1 is a sample plot of the voltage-current relationships for various EMLs generated from Table 3.

Table 1. Force, current, and voltage relationships for various electromagnetic launchers with constant driving current

Launcher Type	Driving Force	Back EMF	Normalized Driving Voltage (V/v)	Assumptions
• $t_c >> t_\ell$				
SOLENOID GUN	$\frac{1}{2} I^2 \frac{\partial L_s}{\partial x}$	$I \frac{\partial L_s}{\partial x} v$	--------*	$I = I_s = I_A$, L_A = Const.
• $t_c = t_\ell$				
RAILGUN	$\frac{1}{2} I^2 \frac{\partial L_s}{\partial x}$	$I \frac{\partial L_s}{\partial x} v$	$I \frac{\partial L_s}{\partial x}$	$I = I_s = I_A$, L_A = Const.
HELICAL RAILGUN	$I^2 \frac{\partial M}{\partial x}$	$I \frac{\partial M}{\partial x} v$	$I \frac{\partial M}{\partial x}$	$I = I_s = I_A$, L_A = Const. L_s = Const.
• $t_c < t_\ell$				
MASS DRIVER	$I_s I_A \frac{\partial M}{\partial x}$	$I_A \frac{\partial M}{\partial x} v$	$I_A \frac{\partial M}{\partial x} + \frac{L_s I_s}{\ell}$ *	L_A = Const. , L_s = Const.
INDUCTION ACCELERATOR	$I_s I_A \frac{\partial M}{\partial x}$	$I_A \frac{\partial M}{\partial x} v$	$I_A \frac{\partial M}{\partial x} + \frac{L_s I_s}{\ell}$ *	L_A = Const. , L_s = Const.

*See text

Table 2. Typical electromagnetic parameters for EMLs

Launcher Type	$\frac{\partial L_s}{\partial x}$ (H/m)	$\frac{1}{N_s N_A} \frac{\partial M}{\partial t}$ (H/m·t^2)	L_s/ℓ (H/m)	Other Assumptions
• $t_c >> t_\ell$				
SOLENOID GUN	1.0×10^{-4}	3.5×10^{-6}	---	---
• $t_c = t_\ell$				
RAILGUN	4.5×10^{-7}	---	---	---
HELICAL RAILGUN	---	2.5×10^{-6}	---	$(N_s) \cong (N_A)$
• $t_c << t_\ell$				
MASS DRIVER	---	2.5×10^{-6}	5.5×10^{-5}	$I_s N_s \cong I_A N_A$
INDUCTION ACCELERATOR	---	5.0×10^{-6}	5.5×10^{-5}	

Table 3. Derived ideal driving current and voltage requirements for EM launchers (based upon assumptions in earlier tables)

Launcher Type	Driving Current (A/MN)	Driving Voltage (Volts/(MN·m/s))
• $t_c \gg t_\ell$		
SOLENOID GUN	1.4×10^5	------*
• $t_c = t_\ell$		
RAILGUN	2.1×10^6	0.95
HELICAL RAILGUN	$\frac{6.3 \times 10^5}{N_s}$	$1.6\ N_s$
• $t_c \ll t_\ell$		
MASS DRIVER	$\frac{6.3 \times 10^5}{N_s}$	$1.6\ N_s + \frac{35}{N_s}$
INDUCTION ACCELERATOR	$\frac{4.5 \times 10^5}{N_s}$	$2.3\ N_s + \frac{25}{N_s}$

*See Text

Such figures are useful for evaluating relative power supply requirements for the various EMLs for specific missions. If, for example, the requirement was for a launcher to provide an 0.1-MN force to a terminal velocity of 10^4 m/s, the generalized graph in Fig. 1 can be readily modified to this specific task by altering the axes appropriately (see Fig. 2). Then, if a candidate power supply for the task is a 20-kV, 10-kA capacitor bank of appropriate energy, this capability can be easily mapped onto the launcher requirements (see Fig. 2) to determine compatibility.

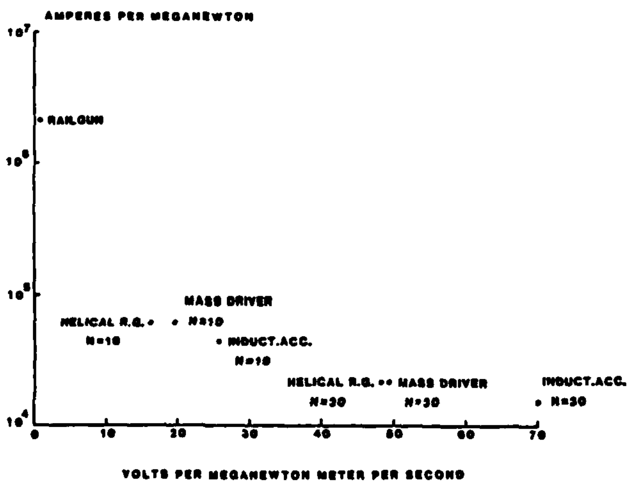

Fig. 1. Generalized voltage-current requirements for various EM launchers

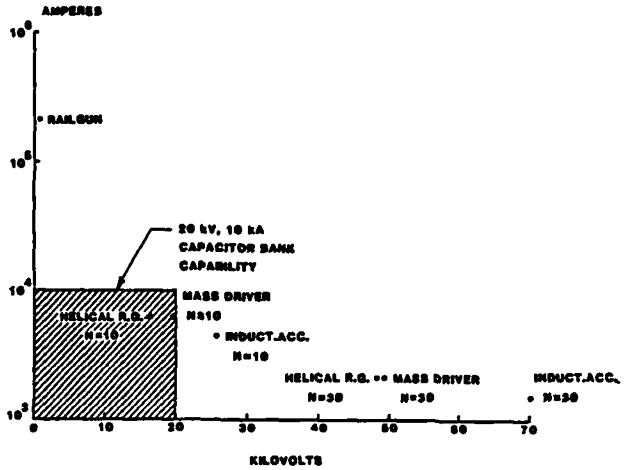

Fig. 2. Task specific voltage-current requirements for 0.1-MN, 10-km/s EM launchers

On the other hand, if other considerations dictate that a mass driver must be used, then the voltage-current range in which the power supply must operate quickly becomes apparent.

Conclusions

Scientists and engineers of various backgrounds and disciplines have contributed to the rapid growth of the EML technology base. Although this varied input is essential to the strength of the community, it is inevitable that each contributor describes concepts in terms of his or her own background. This often results in confusion and makes comparisons between EMLs difficult.

While certainly not complete, this paper represents another step in a continuing attempt to establish a common basis for comparison between the various EML concepts and requirements. In this case the basis is power supply requirements that are often the limiting technology.

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